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PETROGRAHIC FEATURES AND PHYSICAL PROPERTIES OF CERTAIN TRAVERTINE BUILDING STONES

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Travertine stone is widely used in the cultural heritage, mainly throughout the Mediterranean area. In this paper, we have studied two varieties of Spanish coloured travertines from the Betic Zone, marketed as Red Alhama (from Alhama de Almería) and Golden Travertine (from Albox, Almeria province); a grey limestone with tufa facies used in the city of Velencia's architectural heritage (Godella stone); and a white Turkey travertine, which is largely marketed as Classic Travertine and is commonly imported by Levantina S.A.

Several physical properties of travertines are characterised and linked to their fabric: dry bulk density, open porosity (P) and capillary absorption coefficient. Determination of strength was performed using dry uniaxial compressive strength (UCS) and ultrasonic tests. The ultrasonic transmission method was used to obtain compressional (vP) and shear waves (vS) as well as the anisotropy coefficient.

The travertines studied are mainly composed of calcite (>95%) and show several petrographic facies, which can be classified as travertine and tufa. Travertine is formed by parallel layers of limestone (bedding) and several different facies or fabrics are distinguished: porous, massive, laminated and cryptolaminated. Tufa or tufaceous limestones show homogeneous porous tufa facies and complex tufa facies with stromatolitic structures. Thus, the Red Alhama travertine studied presents mainly laminated and cryptolaminated facies (P =5 .48±0.43%), as well as homogeneous porous tufa facies (P = 31.72±3.03%). The Golden Travertine studied mainly presents porous travertine facies (P = 11.82±4.05%); the studied Godella stone shows complex tufa facies (P = 29.89±3.69%); Meanwhile in the White Turkey travertine massive facies (P = 6.79±0.05%) predominate.

The petrophysical properties of the travertines depend greatly on their facies. Thus, low-porous or massive travertines showed the highest mechanical resistance, for example, in the White Turkey travertine, UCS = 41.89±9.90 MPa, vp = 4946.34±211.49 m/s and vs= 2851.13±76.17 m/s, measured in the perpendicularly to sedimentary structures, whilst the high-porous tufa facies were the least resistant, for example, in the Godella Stone, UCS = 15.97±5.74 MPa, vp = 4390.21±0.32 m/s and vs = 2395.01±272.12 m/s. The laminated facies reveal the most anisotropic behavior, which is clearly displayed in the capillary and mechanical properties.

Moreover, it is important to highlight the low influence of sedimentary structures on the mechanical properties (strength and ultrasonic velocity), either parallel or perpendicular to bedding and/or lamination on the unweathered stone. This fact corroborates the good performance of travertine as a dimensional stone.

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INFLUENCE OF MESOFABRIC ON WATER TRANSPORT PROPERTIES OF CONTINENTAL LIMESTONES

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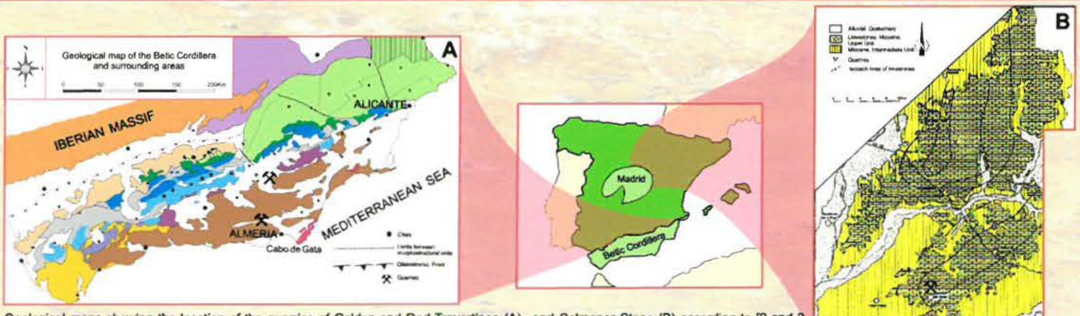
1 INTRODUCCTION

The influence of mesofabric or sedimentary structures on water transport properties (WTP) was assessed in Spanish coloured travertines from the Betic Zone (Red Alhama and Golden Travertine from Albox), in a white Turkey travertine and in Colmenar Stone. As regards the first two types of stone, their petrological and petrographic characteristics are described in detail by García-del-Cura et al. [1]. Colmenar Stone is a white biogenic lacustrine limestone largely used in the cultural heritage of Madrid, in sculptures and buildings.

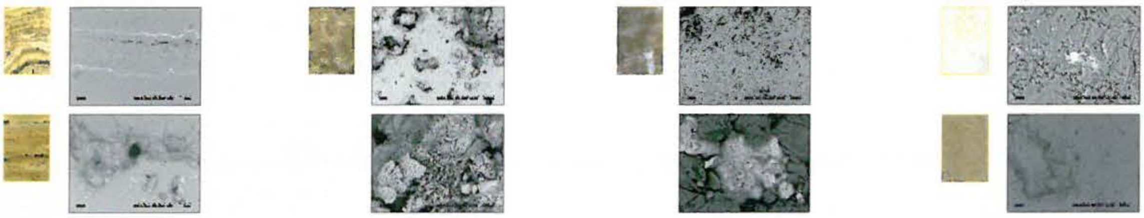


Geological maps showing the location of the quarries of Golden and Red Travertines (A) and Colmenar Stone (B) according to [2 and 3, respectively]

2 MATERIALS AND METHODS

DESCRIPTION

MATERIALS



Figures. Scanned and SEM-bse images of the travertine and tufa facies studied.

METHODS

The experimental procedure consisted of two stages: (1) pore structure and (2) hydrical properties characterization. The pore structure characterization and the capillary absorption coefficient were performed using prismatic samples (4x4x4 cm), whilst the samples used for permeability experimental procedure were cored from prismatic samples (7x7x14 cm), from parallel and perpendicular bedding of limestones. Thus, the water permeability was on cylindrical rock samples (3 cm in diameter and 6 cm in height).

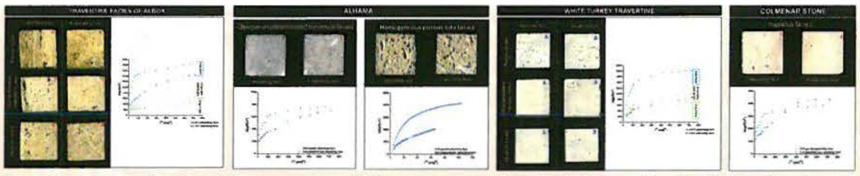
(1) Pore structure

Pore structure was described in terms of porosity, including total, $Ø_T$, and effective porosity, $Ø_{vs}$. $Ø_T$ is defined as the ratio of the volume of the pore space/ bulk volume of the material and can be expressed as ratios of densities [4]. Solid density, ρ_s, was obtained through Helium pycnometer tests using an AccuPyc 1330 device and bulk density, ρ_b, was calculated by direct measurements of sample dimensions. $Ø_{vs}$ was performed according vacuum saturation porosity test.

(2) Hydraulic properties

Hydrical properties were analysed by means of the capillary imbibition test [5] and water permeability test performed using the steady-stay flow methods. Prior to the permeability test, the samples were dried at a temperature of 70 ºC for 48 hours until constant mass was achieved. This sample was then saturated according to the vacuum saturation test. Finally, it was placed in a triaxial cell. Thus, water permeability was estimated using Darcy's Law, when the steady-stay flow was achieved, in other words, when both the water inflow and outflow were equal.

3 RESULTS AND DISCUSSION



Figures. Experimental weight of absorbed water per unit area, M(t)/S versus square root of time, $t^{1/2}$ (right) of travertine and tufa facies obtained from their two orthogonal directions (paralell, //, and perpendicular, ⊥, to the bedding/porosity).

The open porosity, $Ø_{vs}$, shows a good linear correlation with permeability coefficient, k, obtained using the steady-stay flow methods. The fabric or facies strongly influences porosity and WTP behaviour (permeability and capillary absorption coefficient, C, of continental carbonate rocks. Thus, the massive facies registered the lowest physical property values, for example, in the Colmenar Stone, whilst homogeneous porous tufa facies showed the highest values.

Table. Bulk density, ρ_b, total, $ø_T$, and effective, $ø_{vs}$, porosity, capillary connected porosity, $ø_c$, capillary absorption coefficient, C, permeability, k, and anisotropic coefficient, A, values of travertine and tufa facies.

Physical properties	Albox						Alhama		White Turkey travertine						Piedra de Colmenar
	Travertine facies						Travertine facies (oblique cryptolaminatod)	Homogeneous tufa facies	Travertine facies						
	Massive facies		Porous facies		Cryptolaminated massive facies				Massive facies		Porous facies		Cryptolaminated massive facies		
	//	⊥	//	⊥	//	⊥			//	⊥	//	⊥	//	⊥	
ρ_b (g/cm³)	2.42 ± 0.06		2.21 ± 0.19		2.45 ± 0.11		2.54 ± 0.01	1.71 ± 0.14	2.47 ± 0.01		2.44 ± 0.06		2.48 ± 0.01		2.59 ± 0.03
$Ø_T$ (%)	10.15 ± 2.14		17.98 ± 8.09		9.36 ± 3.75		6.19 ± 0.39	36.36 ± 6.07	6.85 ± 0.4		7.69 ± 2.69		5.75 ± 0.3		3.84 ± 1.19
$Ø_{vs}$ (%)	9.41 ± 1.85		16.63 ± 7.41		8.82 ± 3.28		5.77 ± 0.36	33.55 ± 7.58	6.36 ± 0.3		7.39 ± 2.27		5.43 ± 0.33		3.46 ± 1.21
$Ø_c$ (%)	5.23 ± 1	4.52 ± 1.07	8.98 ± 4.07	7.7 ± 4.38	7.4 ± 1.01	6.07 ± 1.07	1.69 ± 0.15	18.97 ± 4.58	1.76 ± 0.04	1.98 ± 0.06	4.61 ± 0.07	2.26 ± 0.07	2.60 ± 0.05	2.65 ± 0.04	1.11 ± 0.38
C [g/(m²·s^0.5)]	7.7 ± 3.02	3.77 ± 1.36	98.44 ± 52.24	43.97 ± 31.12	8.5 ± 2.03	4.07 ± 0.08	2.18 ± 0.76	183.42 ± 80.77	1.75 ± 0.09	1.89 ± 1.03	6.76 ± 1.02	2.64 ± 0.07	2.24 ± 0.05	1.16 ± 0.04	1.61 ± 0.68
A_C (Dimensionless)	0.57		0.6		0.51		0.54	0.63	0.97		0.27		0.52		
k min. k max. (mD)	0.005 1.344	0.003 0.071	2.699 >500	0.015 0.018	0.011 0.093	0.008 0.009	0.0289 0.1131	4.167 >500	0.174 1.123	0.0019 0.005	0.085 53.696	0.003 0.006	0.078 0.114	0.006 0.008	0.001 0.009
A_K (Dimensionless)	1.61				0.82			0.019	0.04		0.01		0.08		

In travertine facies, WTP are highly conditioned by sedimentary structures (parallel bedding of limestone). C and k coefficients are much higher in the direction parallel to the bedding, increasing the anisotropy. This may lead to weathering processes related WTP in the parallel direction as well as to reduced mechanical resistance. Cryptolaminated facies show lower C and k values than laminated facies, due to the varying limits between adjacent beddings and, consequently, to the low associated open porosity.

Additionally, two particularly important aspects were revealed in this research. On the one hand, WTP do not obey sedimentary structure directionality in either laminated facies with fenestral porosity perpendicular to the bedding, for example in the specific case of Albox, or cryptolaminated facies with fenestral porosity placed as parallel tubes, e.g. Alhama. Thus, water distribution is greatly influenced by the orientation of porosity, increasing in a parallel direction and providing the rocks with anisotropic water distribution on both saturated (permeability) and unsaturated media (capillarity).

Finally, the WTP behaviour of homogeneous porous tufa facies is also restricted by the spatial distribution of framework porosity. The influence of fabric porosity on WTP behaviour may also be significant in diminishing the stone's mechanical properties in the most absorbing directions before the weathering processes.

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We have studied two varieties of Spanish coloured travertines from the Betic Zone, marketed as Red Alhama (from Alhama de Almería) and Golden Travertine (from Albox, Almería province); a grey limestone with tufa facies used in the city of Valencia's architectural heritage (Godella stone); and a white Turkey travertine.

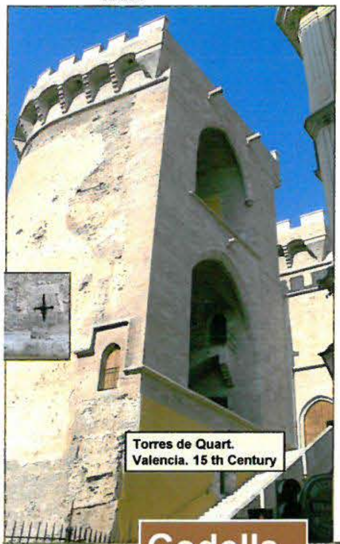
Travertine is used in the Comunitat Valenciana from Middle Ages to recent time.

Structures

- Laminated
- Bedded (1)
- Massive

Textures:

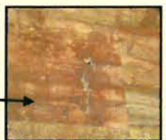
- Arborescent (2) ("Stromatolitic")
- Porous tufa facies:
  - *Homogeneous*
  - *Complex*
- Intraclastic



Torres de Quart. Valencia. 15 th Century

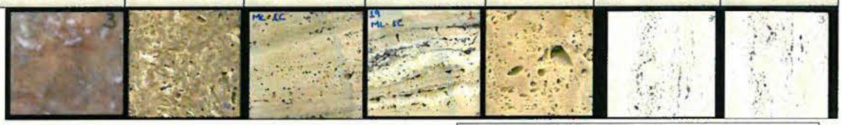
La Lonja. Valencia. 15-16 th Centuries

Alicante 20th Century

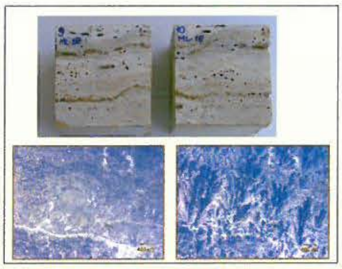


Paving of Airport. Barcelona. 20th Century

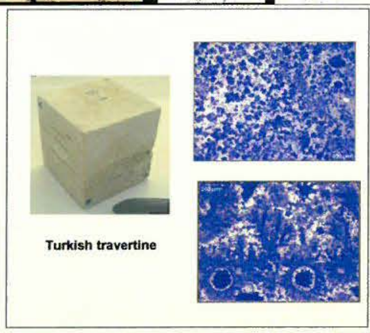
STONE PROPERTIES	Alhama *Travertine facies (cryptolaminated)*	Alhama *Homogeneous porous tufa facies*	Albox *Travertine facies (laminated massive/porous)*		Godella *Complex tufa facies*	Turkish travertine *Travertine facies (laminated massive/porous)*	
			parallel	perpendicular		parallel	perpendicular
Bulk density (g/cm³)	2.51 ± 0.01	1.72 ± 0.11	2.34 ± 0.06		1.81 ± 0.11	2.46 ± 0.05	
Open porosity (%)	5.48 ± 0.43	31.72±3.03	11.82 ± 4.05		29.89 ± 3.69	6.79 ± 0.05	
Uniaxial compressive strength (MPa) UNE-EN 1926:2007	49.48 ± 10.36	12.27 ± 4.50	43.18 ± 14.07	36.82 ± 3.70	15.97 ± 5.74	39.62 ± 12.64	41.89 ± 9.90
Compressional wave velocities, Vp (m/s)	4073.53 ± 112.30	4395.51 ± 160.28	5629.26 ± 154.02	5286.92 ± 112.46	4390.21 ± 0.32	5070.02 ± 261.62	4946.34 ± 211.49
Shear wave velocities, Vs (m/s)	2234.94 ± 17.41	2372.19 ± 148.94	3065.15 ± 73.87	2934.32 ± 56.32	0.95 ± 0.02	2873.04 ± 96.26	2851.13 ± 76.17



Travertine from Alhama de Almeria



Travertine from Albox



Turkish travertine

Uniaxial compressive strength

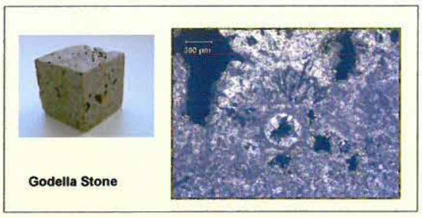
Laminated (perpendicular)

Laminated (parrallel)

Massive

Complex tufa facies

Massive tufa facies



Godella Stone

CONCLUSIONES:

- **Travertine show variated structures and textures.**
- **Mechanical properties are mainly related to structures**
- **The laminated facies reveal the most anisotropic behavior, which is displayed in the physical properties.**
- **Compressional and shear wave velocities are the physical properties more influenced by the anisotropy of the stone.**

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